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AGARD ADVISORY REPORT 299

Technical Evaluation Report on the Fluid Dynamics Panel Symposium on Vortex Flow Aerodynamics

(L'Aérodynamique des Ecoulements Tourbillonnaires)

This Advisory Report was produced at the request of the Fluid Dynamics Panel of AGARD.

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Technical Evaluation Report on the Fluid Dynamics Panel Symposium on

Vortex Flow Aerodynamics

(L'Aérodynamique des Ecoulements Tourbillonnaires)

by
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This Advisory Report was produced at the request of the Fluid Dynamics Panel of AGARD.

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High Angle of Attack Aerodynamics
AGARD CP-247, January 1979

Foreword

This report reviews and evaluates the AGARD Fluid Dynamics Panel Symposium entitled "Vortex Flow Aerodynamics" held 1st—4th October 1990 in Scheveningen. The Netherlands. The purpose of the Symposium was to provide a review of the understanding and prediction of separation-induced vortex flows and their effects on vehicle performance, stability, control, and structural design loads.

The evaluator summarizes each of the papers and relates their contributions and the discussions to some important aspects of vortex flow aerodynamics. He describes where significant progress has been made in major areas of interest including vortex development and burst, modeling and validation of the full range of analytical methods, slender-body flows at high angles-of-attack, vortex control and management, and unsteady vortex flow effects; and where continued work is needed.

The papers presented at the Symposium and the results of the Round Table Discussion recorded at the end of the Symposium are published in AGARD Conference Proceedings CP-494.

J.F. Campbell A.D. Young
Co-Chairmen

Avant-Propos

Ce rapport examine et evalue le symposium organise par le Panel AGARD de la Dynamique des Fluides sur "L'aérodynamique des ecoulements tourbillonnaire" du 1 au 4 octobre 1990 à Scheveningen au Pays Bas. Le symposium a eu pour objectif de presenter une revue des connaissances actuelles dans le domaine des écoulements tourbillonnaires déclenchés par le decollement et leur prediction. Leurs effets sur les performances, la stabilité et le contrôle des véhicules aériens, ainsi que sur les charges de calcul de structure ont ete examines.

L'évaluateur résume chacune des communications présentées et établit le rapport entre les présentations et les débats d'une part et certains aspects importants de l'aérodynamique des écoulements tourbillonnaires d'autre part. Il décrit les progrès réalisés dans les principaux domaines d'intérêt y compris le développement et l'éclatement des tourbillons, la modélisaion et la validation de toute la gamme des méthodes analytiques, les écoulements autour des corps effilés à des grands angles d'attaque, le contrôle et la gestion des tourbillons et les effets des écoulements tourbillonnaires instationnaires. Il signale, également, les domaines où des travaux de recherche resteraient à réaliser.

Les communications presentées lors du symposium, ainsi que les conclusions de la table ronde qui l'a clôturé sont publiés dans le document AGARD CP-494.

J.F. Campbell/A.D. Young
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Contents

FLUID DYNAMICS PANEL SYMPOSIUM 'VORTEX FLOW AERODYNAMICS' TECHNICAL EVALUATION REPORT

by

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SUMMARY

'Vortex Flow Aerodynamics' is the title of the symposium held by the Fluid Dynamics Panel of AGARD in The Hague, the Netherlands, in October 1990. The proceedings are available as AGARD-CP-494. The principal emphasis of the meeting was to be on the understanding and prediction of separation-induced vortex flows and their effects on vehicle performance, stability, control and structural design loads. This report shows that substantial papers covering this area were attracted from a wide range of countries, together with an attendance even more widely drawn. In itself, this testifies to the current interest in the subject and to the appropriateness of the Panel's choice of topic and approach. An attempt is made to summarize each paper delivered, and to relate the contributions made in the papers and in the discussions to some of the important aspects of vortex flow aerodynamics. This reveals significant progress and important clarifications, but also brings out remaining weaknesses in predictive capability and gaps in understanding. Where possible, conclusions are drawn and areas of continuing concern are identified.

1 INTRODUCTION

The Symposium was held in a hotel in Scheveningen, the Netherlands, from the 1st to the 4th of October 1990. The Fluid Dynamics Panel arranges two symposia a year, divided roughly equally between topics close to areas of application and topics which expose fundamental problems. This one, on vortex flow aerodynamics, was clearly aimed at a range of fundamental problems. A strong programme committee, drawn from the membership of the FDP, was set up under the leadership of Dr Campbell and Prof Young. Its members, listed in Appendix A, come from nine AGARD nations.

The need for the meeting is clearly stated in the call for papers and the programme:

'Separation-induced vortex flows are an important part of the design and off-design performance of fighter aircraft, missiles, and space-plane concepts. A better understanding is needed in order to predict and control these vortex flows throughout the flight envelope at subsonic, transonic, and supersonic speeds, and especially during high-lift operations for take-offs and landings and sustained and instantaneous manoeuvres.'

Alongside the need for a better understanding is the need for a predictive capability which leads to improved performance and manoeuvrability, to reduced development time and cost, and to longer aircraft life. To quote again from the call for papers:

'A wide range of methods are used at present to calculate separation-induced vortex flows. Theory-experimental (wind-tunnel and flight) comparisons are required to establish the value of these methods for various flow regimes so far as basic physics and applications are concerned. The problem of scaling wind-tunnel results to flight conditions also deserves specific attention.'

These general considerations led to the identification of four specific topics which the organizers hoped would be covered by presentations:

'Vortex fundamentals, including boundary-layer separation lines on wing surfaces and edges, vortex development and burst, vortex cores, sheets, and filaments, vortical flow interactions with each other and with the flow over neighbouring surfaces, which include multiple vortices, shock waves, and mixtures of attached and vortex flows.'

'Prediction and measurement of vortex flows including their modelling by, and validation of, the full range of analytical methods, including empirical, vortex sheet panelling techniques, and Euler and Navier-Stokes equations, the application of vortex dynamics to time-variant flows, and the latest experimental results and techniques developed in wind tunnels and in flight, including surface and off-body flow visualization and measurement by laser.'

'Application of vortex flows to the design and performance of aeroplanes, including Reynolds number and Mach number scaling, geometry effects of wing-body, strake, and aft tails, vortex control and exploitation, and vehicle stability, control, and structural design loads.'

'Unsteady aerodynamic effects associated with vortex flow movements in manoeuvring and oscillatory motions, instabilities and bursting.'

With a view to achieving this coverage, six active workers in the field were persuaded to deliver invited papers, to which somewhat more generous time allowances were given. These are the papers numbered 1, 6, 12, 20, 25 and 26 in the list of papers, reproduced here as Appendix B.

The decision to choose vortex flow as the symposium topic was timely not only for the reasons stated above, but also because of the information which was becoming available. This arose, as usual, from individual studies and national programmes, and also, unusually, from two international programmes. The first of these is the International Vortex Flow Experiment (which actually involved several experiments and some computation) planned and executed in Germany, the Netherlands, Sweden and the USA. The second, in which computational activity dominates, is an exercise involving Germany, Italy, the Netherlands, and the UK, under the auspices of the IEPG. Both these programmes centred around wing flows, basing themselves initially on the relatively simple case of the cropped delta wing, but taking on board the complexities of transonic flow development.

The evaluation undertaken in this report attempts to cover three aspects. Section 2 addresses organizational

aspects, including an analysis of the origins of the papers and participants. The longest section, the third, comprises resumés of all the papers delivered, based on the oral presentations, the available written versions, and the speakers responses to questions. This provides a record of the proceedings and establishes the technical level of the meeting. In section 4 assessments are provided of the contributions made by the papers and the general discussion to a number of key issues. This establishes the relevance of the meeting and demonstrates that the aims of the FDP and the Programme Committee were met. Finally, some conclusions and recommendations arising from the meeting are presented in section 5.

2 GENERAL COMMENTS ON THE MEETING

The programme for the meeting listed 33 papers (see Appendix B), coming from nine countries, of which 32 were delivered and proved to be of interest to the audience. The content of each is outlined in section 3 of this report, and their relevance to key issues in the field is brought out in section 4. It is regrettable that paper 6, by Dr Luckring of NASA Langley, was not given, since he was unable to attend. However, it is available in the Conference Proceedings (CP-494). This is an invited paper, in the important area of computational fluid dynamics (CFD), and it would have complemented Dr Hoeijmakers' invited paper, which dealt in detail with inviscid methods and European work, by dealing in detail with Navier-Stokes calculations and US work. Such a presentation would have been most valuable, in view of US strength in CFD and the great interest aroused by the results of the Navier-Stokes calculations that were presented. Although the subject matter of the papers varies widely, a contributor to the general discussion pointed out that there were other important manifestations of vortex flow in aerodynamics which were not covered. He would have liked to see papers on propellers and helicopter rotors, as well as more papers on vortex flow about missiles.

The meeting attracted 136 participants from 12 AGARD countries, plus Australia and Sweden. The more active countries (France, Germany, the Netherlands, UK and USA) sent about 20 each, with smaller numbers from the remainder. Forty-four of the participants came from universities and colleges, 28 from manufacturing industry, and the remainder from government service and research and support agencies. It is disappointing that the attendance from manufacturing industry is so small, in view of the importance of vortex flow for current projects. Of the listed participants 63 are authors of papers, an average of two per paper, and 43 are members of the FDP, an average of 3.5 per country.

Copies of the written versions of the papers were not available to participants in advance of the meeting. Some years ago it was the practice to send out volumes of conference pre-prints before the meeting, which allowed participants to prepare themselves for the event. There are serious difficulties in persuading authors to submit material in advance, but it would be worth considering whether copies of the abstracts, on the evidence of which papers are accepted, could be sent out to participants. There were a few presentations for which written versions were not available at the meeting itself. This is unfortunate, because the availability of papers, through participants, in advance of the publication of conference proceedings is one of the attractions for an organization contemplating sending a representative to a meeting. All the oral versions were well presented, though many of the slides and viewfoils were less clear than they might have been. The weaknesses are the usual ones: lines too thin, lettering, numbers and symbols too small. In years gone by, advice on these points was sent to authors, and it might be worth resuming the practice.

A difficulty with meetings that aim at a general audience but offer a substantial number of CFD papers is that many participants find them unattractive, tending to arrive late or leave early to avoid them. This tendency was not apparent at this meeting, perhaps because the titles of the papers referred to delta wings, vortices and the like. Certainly the presentations concentrated on results rather than techniques, to the satisfaction of the undedicated section of the audience. Perhaps the presenters themselves for once found the results more interesting than the methods, a tribute to the fascination of vortex flows.

Since the aims of the meeting covered understanding as well as knowledge, it is important that the discussion time and facilities were adequate and that good use was made of them. Speakers and chairmen kept to schedule, so that there was time for questions at the end of individual presentations. Speakers dealt with questions frankly and as fully as time allowed. Adequate time was allocated to coffee, lunch and tea breaks in which points could be pursued at greater length. A final general discussion period at the end of the meeting allowed for remaining points to be aired and explanations provided, after people had had time to reconsider their immediate impressions. It also allowed one or two participants to squeeze in a mini-presentation, but there is no security against that hazard. The meeting was fortunate in having Prof Young to introduce and control this general discussion, finding him as acute, alert and supportive a chairman as ever. It was unfortunate in that his co-chairman, Dr Campbell, was prevented from attending by the same budgetary problem that kept Dr Luckring away. He had contributed much to the planning of the meeting and would have contributed to the occasion had he been present.

3 RESUMÉS OF PAPERS PRESENTED

Paper 1. H.W.M. HOEIJMAKERS, from NLR, the Netherlands, gave an invited paper on modelling and simulation of vortex flows in aerodynamics. His written version was not available at the meeting. He covered a range of flow models: Linearized potential flow with embedded vortex elements of sheet and filament forms, the Euler equations with numerically-captured shock waves and vortices, and the laminar and Reynolds-averaged Navier-Stokes equations. From his own investigations and from his involvement in the IVFE and the IEPG exercise he provided a valuable assessment of the current status of methods using these models. Potential flow methods can give a good insight into many fundamental aspects of low-speed vortex flows, excluding vortex breakdown, but the fitting of vortex sheets becomes too complex a process when the configuration concerned is not a simple one. Euler methods are capable of a proper representation of compressibility effects at higher speeds, and can capture reliably vortices formed from sharp edges. For a vortex formed from a smoothly curved surface, even if the separation line is known independently, an adequate model is needed to enforce the occurrence of separation. The adequacy of Euler methods for predicting vortex breakdown is not clear. Navier-Stokes methods have the ability to treat separation from smooth surfaces, but are still too expensive for routine application. It is not clear that existing turbulence models are adequate for separated flows and the prediction of transition will remain an outstanding problem for some time. He emphasized the importance of grid quality and density, regarding adaptation techniques as indispensable; the need

for detailed comparative measurements in real flow fields; the requirement for large memory in computers; and the benefit of displays of the spatial behaviour of computed solutions, requiring extensive post-processing software.

Paper 2. Panel member D.S. WOODWARD, presented this paper by WILLIAMS (RAE UK), KORDULLA (DLR, Germany), BORSI (Aeritalia, Italy) and HOEIJMAKERS (NLR, Netherlands). The paper is a direct outcome of the early stages of an exercise under the European defence procurement initiative known as IEPG. In it calculated results for the flow over a sharp-edged, 65° sweep, cropped-delta wing at M = 0.85 and 10° incidence from seven Euler codes and a Reynolds-averaged Navier-Stokes code are compared with one another and with measurements at a Reynolds number of 9 million on a similar wing mounted on a body. The differences between the Navier-Stokes solution with 2 million cells and the surface pressure measurements are consistent with the configuration difference. All the Euler solutions are obtained on the same grid of 300 thousand cells, and each code is used with the least added dissipation consistent with convergence. All the Euler pressure distributions are similar and differ from the Navier-Stokes solution under the leading-edge vortex, where they show no secondary separation. The five Euler codes which use variants of the same basic algorithm give the most closely similar results, though even among them there is a 3% variation in lift coefficient. Inclusion of a cell-vertex method and an upwind method increases the variation above 4%. For comparison, the lowest Euler lift is 12% above the Navier-Stokes value.

In response to a comment that the C-H topology of the Euler grid is bad for a highly-swept wing, HOEIJMAKERS replied that a quasi-conical grid gives similar results except near the wing apex. Someone asked how the calculated total pressure could exceed the free-stream level, and it was explained that the computations had sources of error distinct from the artificial viscosity and these might not be dissipative.

Paper 3. This paper, by BORSI, FORMAGGIA, HELTENA, SANTILLAN, SELMIN and TARDITI of Aeritalia, Italy, presented solutions of the Euler equations on structured and unstructured grids for the vortex flow over a sharp-edged cropped-delta wing and body at M = 0.85 and 10° incidence. The structured grid is generated algebraically, using a multi-block technique, and contains over 300 thousand cells in 12 blocks. The unstructured grid is generated initially by a front-advancing technique, leading to a coarse grid of 30 thousand nodes, followed by a grid-refinement technique. This sub-divided the grid wherever the entropy calculated on the coarse grid deviated significantly from the free-stream level, giving 55 thousand nodes. The solution on the refined grid shows a higher and narrower suction peak beneath the leading-edge vortex. The results on the structured and refined unstructured grids are described as comparable, thus confirming the value of the unstructured approach. However, the difference between the surface pressures calculated using the structured and unstructured grids could be significant and it is not clear which is more accurate. The authors feel the need for further studies of the effects of grid density over the vortex region and for future research into adaptive strategies.

A questioner took up the last point, querying a strategy based on entropy variation, since the exact inviscid solution should avoid the generation of entropy in the vortex.

Since in this paper the body as well as the wing of the IVFE is represented, its results should clarify whether the discrepancies reported in the previous paper between Euler calculations and experiment stem primarily from failure to represent the body or from the inadequacy of the inviscid model.

Paper 4. J.I. van den BERG presented a paper by herself, JACOBS and HOEIJMAKERS of NLR, the Netherlands, comparing the results of an Euler calculation method with measurements on the sharp-edged wing of the IVFE at Mach numbers of 0.15, 0.5 and 0.85 and at incidences of 10, 15 and 20°. The comparison was detailed, but no written version was available at the meeting. The solution grid is generated by a multi-block approach, with continuity of grid lines but not of their slopes. About 200 thousand nodes in 16 blocks follow a C-O topology. The algorithm is Jameson, cell-centred. In addition to the differences between calculation and experiment arising from the failure to capture secondary separation, differences in shock patterns appear at M = 0.85, 20°. These are most marked where the shock separated the boundary layer in the experiment. On the other hand, the calculation represents the near-wake well, with the trailing-edge vortex appearing and moving round the leading-edge vortex. A view of the evolution of the flow at 20° incidence with increasing Mach number shows the vortex moving inboard, the pressure distribution becoming more conical, and the appearance of shock waves.

There was some discussion of the significance of a sharp peak in the pressure distribution along the centre line at the wing apex (see paper 15).

Paper 5. E.M. HOUTMAN presented a paper by himself and BANNINK from TU Delft, the Netherlands, describing an experimental and numerical study of the transonic flow over a sharp-edged pure delta wing with 65° sweep. Pressures are measured on the flat upper surface along the centre line and across the 70% lengthwise station, surface oil-flow is recorded, and, at M = 0.85 and incidences of 10 and 15°, the upper-surface flow is traversed with a 5-hole hemispherical probe. The calculation uses a C-O grid with 131 thousand cells, on which the Euler equations are solved by a second-order upwind method, using a 5-level multigrid scheme. Flux splitting and flux-difference splitting algorithms are compared. No additional dissipation is needed, but both algorithms lead to losses of total pressure of about 67% in the vortex core at M = 0.85, 20° incidence. At 10° incidence flux-difference splitting predicts surface pressure rather better than flux splitting, but of course neither does well in the absence of any representation of secondary separation. The calculations fail to predict the vortex breakdown observed at 20° incidence and the higher Mach numbers. A striking Schlieren picture at M = 0.85, 19° incidence, shows two shocks normal to the centre line, with the pressure along the centre line falling rapidly between them, apparently caused by the displacement effect of the broken-down vortices. It is suggested that the shock pattern is caused by the breakdown, rather than conversely.

Paper 6. The scheduled paper by J.M. LUCKRING of NASA Langley, USA, was not given, as he was unable to attend the meeting. It may be found in the Conference Proceedings.

Paper 7. A. HILGENSTOCK gave a paper by himself and VOLLMERS of DLR, Göttingen, Germany on simulating compressible turbulent flows past two delta wings alone and in combination with a fuselage and canard. The two wings share the 65° cropped-delta planform of the earlier papers

and one has sharp and the other rounded leading edges. The Reynolds-averaged Navier-Stokes equations are solved with the Baldwin-Lomax turbulence model. A grid-sensitivity study is based on a comparison at M = 0.85, incidence 10°, between measurements on the sharp-edged wing with a minimal body and calculations on the wing alone using three different grids. The reference grid has 770 thousand nodes and the two different refined grids have each 1.4 million nodes. The configuration difference prevents agreement over the forward part of the wing. Further aft reasonable agreement is obtained with all grids, but refinement normal to the surface of the wing produces improvements in detail, though minor discrepancies remain. The main comparison is between measurements and calculation for the round-edged wing with the body. A more efficient C-H grid topology is used with 1 million nodes. Comparing measurements at a Reynolds number of 4.5 million with calculations in which transition is assumed at 2.5% chord, good agreement is now found forward, but further aft the calculated secondary separation is too early, owing to the overly simple turbulence model. Comparison with NLR measurements at Re = 9 million is less satisfactory. For the wing-canard combination 2 million nodes are used in the calculation. The principal flow features are reproduced, but detailed comparisons of surface pressure distributions are invalidated by the lack of fuselage representation and the assumption of laminar flow in the calculation. Experimental difficulties with laser light sheet and surface oil flow visualization techniques are discussed in the light of computed streamline patterns.

Several comments came from the audience about the mechanisms which lead to the 'hole' in the light sheet near the vortex core.

Paper 8. A. RIZZI of FFA, Sweden gave a paper by himself and MURMAN of MIT, USA on hypersonic leeside vortices on a delta wing. No written paper was available at the meeting. Both Euler and Navier-Stokes calculations are described from both FFA and MIT for a 70° swept delta wing with rounded leading edges at M = 7, an incidence of 30°, a Reynolds number of 6 million and no heat transfer. All the methods predict vortices. The Euler methods used are similar, but the surface streamlines and Mach number distributions they predict are very different. The grid topologies differ, and the flow seems to be very sensitive to the loss in total pressure, 90% of the free-stream total pressure being lost across the bow shock. In contrast, although the Navier-Stokes methods are very different – full at KTH, thin-layer at MIT – the predicted skin-friction is very similar in magnitude and direction. Some differences appear in Stanton number. Experiments show effects of the trailing edge, transition, and vortex breakdown, which are not represented in the calculations; so there are discrepancies in surface pressures and flow field quantities.

Paper 9. U. DALLMAN presented a paper prepared with colleagues HILGENSTOCK, RIEDELBAUCH, SCHULTE-WERNING and VOLLMERS from DLR, Göttingen, Germany on the footprints of three-dimensional vortex flows on blunt bodies. They analyze a number of numerical solutions of the Navier-Stokes equations, laminar and Reynolds-averaged, for separated flows past a circular cylinder and a sphere at low speeds, the round-leading-edge delta wing of paper 7 at transonic speed, and a double ellipsoid at hypersonic speed. These flows are discussed in terms of streamlines, skin-friction lines, vortex lines, and contours of total pressure, entropy, Mach number, vorticity magnitude and heat flux. The relationship between these pictures and the presence of a vortex is discussed, where a vortex is defined to exist wherever the (tensor) gradient of the velocity vector has complex eigen-values. Impressive perspective views of possible three-dimensional flow structures are shown and related to patterns of skin-friction lines. Of particular interest is the view of calculated skin-friction lines near the leading-edge of the delta wing, which shows that the leading-edge separation is of the open type, occurring in the absence of any local topological singularity in the pattern of skin-friction lines. The separation line is clearly defined downstream of the vortex origin, but nothing distinguishes between the skin-friction lines on the upstream side.

Paper 10. N. RILEY described the work done with KIRKKOPRU at the University of East Anglia, UK on secondary separation on a delta wing. This takes the form of an interactive calculation, in which the external flow is represented by slender-body theory and includes a conical vortex-sheet representation of the leading-edge vortex, and the viscous flow is represented by a quasi-conical laminar boundary layer developing outboard of the upper-surface attachment line and extending onto the vortex sheet. The displacement effect of the boundary layer on the external flow is represented by a transpiration velocity on the wing and sheet, while the boundary layer develops, separates and reattaches under the influence of the surface velocity field induced by the outer flow. To avoid the singular behaviour at separation, interaction is allowed for by the quasi-simultaneous procedure of Veldman. In an outer iterative cycle the primary vortex sheet is recalculated. A satisfactory level of convergence is achieved, and results are presented for three Reynolds numbers at one angle of incidence, and for three incidences at one of the Reynolds numbers. The effect of the secondary separation is to displace the primary vortex core inboard and upward, and to change the upper-surface pressure distribution markedly. The peak suction is much reduced, with little recompression outboard of the peak, while the pressure inboard is reduced. A factor of 40 on the Reynolds number has little effect on the wing pressure. Comparison with measured pressure distributions is disappointing, primarily because of the limitations of slender-body theory. It is also likely that transition to turbulence in the separated shear layer will change the reattachment process significantly at wind-tunnel Reynolds numbers. However, the model seems better than previous inviscid vortex-sheet models of secondary separation.

Paper 11. U. KAYNAK gave a paper, with colleagues DINDAR and BARLAS from TUSAS Aerospace Industries, Turkey and TU from NASA, Ames, on the effect of using a non-equilibrium turbulence model for transonic delta wing flows. The turbulence model is a generalization of the Johnson-King model to three-dimensional flow, based on integrating an ordinary differential equation for the maximum Reynolds shear stress in the boundary layer at a point on the surface along a streamline which passes through the point at which the maximum occurs. This model is applied first to two validation cases: the transonic bump configuration of Bachalo and Johnson and the low-sweep, low-aspect-ratio wing of Lockman and Seegmiller. For both, the model gives results which are very different from those given by the usual algebraic equilibrium models and much closer to the experimental results. In contrast, for the 65° delta wing of the IVFE, the pressure distributions computed using the Baldwin-Lomax model and the Johnson-King model are almost identical, with neither being significantly closer than the other to the measured values. The authors conclude that the model is viable for the three-dimensional Navier-Stokes equations, giving increased accuracy for little increase in computational cost. They attribute the insensitivity of the delta wing flow to the dominance of convective processes, leading to little effect of non-equilibrium.

It is noted that the results of this paper differ a little from those of paper 7, agreeing a little more closely with experiment.

Paper 12. D.G. MABEY (RAE, Bedford, UK) gave an invited paper devoted to a review of the aerodynamic topics which emerged at a Specialists' Meeting of the Structures and Materials Panel on 'Aircraft Dynamic Loads due to Flow Separation'. The proceedings of this meeting are available as AGARD-CP-483, 1990. He notes two substantial advances, one in the prediction of limit-cycle oscillations and one in the validation of the linear model for buffeting prediction. He also makes a number of criticisms. Many of these relate to the absence of papers on particular topics, but two concern shortcomings in the way investigations are carried out. The first of these is a failure to present results in a non-dimensional or AGARD standard form. The second is a failure to pay attention to actual or potential scale effect in testing and computation. The most significant papers for the present meeting are two (numbers 10 and 11 in CP-483) on the vortex-induced fin buffet on the F-18 and one (number 14) which tries to indicate the sort of computational resources needed to predict unsteady air loads on complete aircraft in separated flow. To predict buffet excitation on the fins of an F-15 model in one condition was estimated to require 950 hours computation on an advanced machine. The most striking feature of the F-18 flow measurements (from paper 11) is the extremely sharp peaks in the spectra of pressure fluctuations at the angles of incidence for which the fluctuations are strongest.

In response to questions, it was confirmed that the occurrence of the peaks was unexplained.

Paper 13. J.H. DEL FRATE gave a paper with his colleagues FISHER and ZUNIGA from NASA Ames and Dryden, USA on flight experiments on the F-18 High Alpha Research Vehicle and their correlation with tunnel results on a 1/16 scale model. Flow visualization and pressure measurements are included and a movie was shown which included striking sequences of the lateral oscillation of a fin viewed in flight. In-flight surface flow visualization was performed on the forebody and LEX, maintaining uniform flight conditions from the time of the dye release until the medium had dried, and recording the pattern after landing. Vortex cores from the forebody and LEX were made visible using smoke injection, with breakdown and strong interaction clearly visible in the in-flight photographs. The angle of incidence range extends up to 50°, and side-slip up to 7°. The lengthwise movement of vortex breakdown with incidence is very similar in flight and in four ground facilities, covering a factor of a thousand in Reynolds number. Surface pressures generally agree closely between tunnel and flight, though there are some interesting differences which are not readily explicable in terms of configurational and Reynolds number differences. A close correlation between flow visualization and surface pressures in flight extends to the identification of a laminar separation bubble on the forebody in both.

In response to a question, DEL FRATE identified the severest fin buffet as occurring when the breakdown of the LEX vortices reached the leading edge of the wing. Further discussion about the appearance of the discrete frequency in the pressure fluctuations shown in paper 12 led MABEY to insist that no feedback was involved and the fin oscillation was due to buffet only.

Paper 14. H.-CHR. OELKER presented a paper by himself, BERGMANN and HUMMEL of the Technical University of Braunschweig, Germany, on vortex formation over a close-coupled canard-wing-body configuration in unsymmetrical flow. This describes some surprising results obtained in a low-speed wind-tunnel investigation. The wing and canard are pure deltas with 60° sweep mounted in the mid-plane of a pointed body of revolution. The tests use a six-component balance, a large number of pressure orifices, and a laser-light-sheet for flow visualization. The incidence range extends to 40°, with side-slip to 26°. The balance measurements show sudden, almost discontinuous, changes in the aerodynamic derivatives due to side-slip. These jumps occur at angles of side-slip which reduce as the incidence increases. For the canard-off configuration, flow visualization associates the combination of incidence and side-slip at which the jump occurs with vortex breakdown reaching the wing apex on the windward side, and pressure measurements associate this with the collapse of the upper surface flow on the windward side to a deadwater region. With the canard, the changes in derivatives are larger, partly because the favourable interference between the wing and canard vortices is destroyed when breakdown in the wing vortices reaches the apex. Even in laterally-symmetric flow, a bubble-type structure forms in the canard vortices between the canard and wing, perhaps because the favourable pressure gradient over the wing restores an orderly structure after breakdown has been initiated in the canard vortex. This was dramatically illustrated in a movie sequence of a water-tunnel flow visualization, in which dye drained steadily into the revitalized canard vortices from a pocket sitting behind the canard trailing edge.

Paper 15. A. ELSENAAR presented a paper by himself and HOEIJMAKERS of NLR, the Netherlands, on an experimental study of the flow over a sharp-edged delta wing at subsonic, transonic and supersonic speeds. No written version was available at the meeting. The wing is a new model of the IVFE wing, with many pressure orifices, so that more detail of the flow structure could be elucidated. At a Mach number of 0.85 and an incidence of 10° or more, the secondary separation is seen to be shock-induced, with an upstream normal Mach number of 1.3. At low Mach number, a suction peak is measured at the wing apex, like that predicted in paper 4. AT M = 0.85, 10° incidence, the suction is low at the apex and rises along the centre line until a rear shock is encountered. At 24° incidence, vortex breakdown occurs and two shocks appear on the centre line. Thus vortex breakdown can have a larger effect at transonic speeds than at low speeds. However, the occurrence of breakdown is not very sensitive to Mach number. An increase of Reynolds number from 4.5 to 12 million made little difference in the symmetry plane, but strengthened the suction peak associated with the secondary separation in the cross-flow plane. Even with the more detailed measurements, the interaction between the rear shock and the cross-flow shock is not clear.

In discussion, DELERY raised the question of a causal relationship between the rear shock and vortex breakdown, as seen in his work. ELSENAAR said it was not clear whether the rear shock extended as far outboard as the vortex and suggested it might be a 'chicken and egg' controversy. HITZEL recalled that DELERY'S experiment involved a vortex in isolation and commented on the ability of computation to predict much of what was seen, supplementing it with values of Mach number normal to isobaric surfaces.

Paper 16. G. PAILHAS described an experimental investigation of a boundary layer developing downstream of a leading-edge vortex, in a paper with COUSTEIX, also of ONERA/CERT, Toulouse, France. The vortex forms on the upper surface of a wing panel of 200 mm chord, swept through 60°, with a round leading-edge, extending right

across a low-speed wind tunnel, at an incidence of 15°. Detailed surface pressure distributions are obtained by translating the model lengthwise and reading from several rows of orifices. The boundary layer near the reattachment line is so thin that only a single hot-wire probe can be used in it. Mean velocity is found by rotating the probe for maximum signal, giving both magnitude and direction, but turbulence measurements there are confined to the mean flow direction. In the vortex, measurements of all three shear stress components are made with a four-wire probe. The main findings are that the boundary layer near the line of reattachment is very thin, that the level of turbulence in it is of the same order as that in a classical boundary layer, and that the three-dimensionality, turbulence and shear which accompany vortex flow are confined to the region in which the leading-edge vortex forms and develops, while the boundary layer is regenerated at the reattachment line.

Paper 17. P. CHAMPIGNY described an experimental study leading to modelling of the vortex flow over a missile fuselage, in a paper with BAUDIN, also of ONERA, Chatillon, France. Measurements are made with ten 5-hole probes mounted on a rake which rotates about the axis of an ogive-cylinder and extends radially for three cylinder diameters. Data are taken at 5° intervals in roll angle, the probe diameter is 3 mm, the body diameter is 100 mm and its length is 15 diameters. The range of incidence extends to 20° at Mach numbers of 0.8, 1.5, 2 and 3, and Reynolds numbers of around a million, based on cylinder diameter. Flow variables on a finer grid are obtained by interpolation. As the incidence increases, vortices form closer to the apex, the relation being independent of Mach number. The vortex positions are found to depend on the product of their distance downstream of their origin and the sine of the incidence, with the vortices rather further from the body when the speed is supersonic. The circulation of the vortices, referred to the cross-flow velocity and cylinder diameter, correlates with the same parameter, as does their core radius. The losses of stagnation and dynamic pressure in the core depend on Mach number, but not on incidence. These correlations allow the flow field around the fuselage to be modelled in terms of potential flow and vortex contributions, leading to a satisfactory agreement between the measured and modelled distributions of local flow direction. The model is applied to calculate the lift acting on a wing panel and the efficiency of an air intake. In both cases the inclusion of the vortex contribution brings about a significant improvement in the predictions. Further studies of the flow near the separation lines are recommended.

Paper 18. M. PIDD presented a paper by himself and SMITH, of RAE, Farnborough, UK, on asymmetric vortex flow over circular cones. This covered an extension of earlier theoretical work with a simple model of the flow, using slender-body theory with two line-vortices in a conical configuration, and a presentation of experimental measurements made in a large low-speed wind tunnel by Fiddes, Lean and Moir. The theoretical work sought to display all the solutions, symmetric and asymmetric, of the flow model, for fixed, symmetric separation lines; and to examine the stability of these solutions to small, asymmetric, non-conical, spatial disturbances. The essential outcome is that for each combination of an incidence parameter and separation line position, there is a single stable solution, provided the incidence parameter is large enough. For a range of values of incidence parameter just above this lower limit, the stable solution is symmetric, while for larger values it is asymmetric. In contrast, the experiments showed many values of side force lying between the extreme values to port and starboard which are all the theory predicts. On a 10° cone, at 35° incidence the measurements are consistent with flows which evolve towards conical extreme states in the downstream direction, but at 30° incidence a variety of non-conical flows arise, with no marked tendency to evolve towards an extreme state. An attempt is made to relate this behaviour to a basically non-conical flow at the apex of the cone and the magnitude of the real part of the dominant eigen-value of the stability analysis.

Paper 19. I.R.M. MOIR, of RAE, Farnborough, UK presented an experimental investigation of the effect of fineness ratio on the side force on slender pointed bodies of revolution. Nine bodies, providing combinations of three different nose angles with three different fineness ratios, are tested at incidences up to 38°, at low Mach number, and at Reynolds numbers from 0.35 to 2 million based on body diameter. Overall force measurements are supplemented by observations of surface oil-flow to assess the length of body affected by flow asymmetry. Roll angle is varied in steps of 10°. The onset incidence, at which significant side force first appears, depends largely on fineness ratio when the nose angle is large. For small fineness ratio, the onset angle depends more on nose angle. Asymmetry appears first at the rear of the body and moves forward as the incidence increases, more rapidly on the bodies with smaller nose angle. The sense of the asymmetry depends on the roll orientation of the nose, rather than that of the afterbody, even when the flow at the nose appears to be symmetrical. The side force is very similar at Reynolds numbers of 1.3, and 2 million. At 0.7 million the onset incidence is the same but the level reached is lower. At 0.35 million measurement difficulties arise, but the onset incidence is apparently increased and the level reached is higher.

In the discussion it was suggested that asymmetry would appear first on the sting supporting the model, but it was felt this was unlikely to affect the flow over the model to any significant extent.

Paper 20. J. DELERY, of ONERA, Chatillon, France, gave an invited paper on the physics of vortex flows. This comprises a very clear account of three-dimensional separation based on the critical points of the pattern of skin-friction lines on the body surface, a description and interpretation of a large number of particular separated flows in terms of these critical points, and some observations about vortex breakdown. The account of separation is essentially that given by Legendre and restated by Lighthill, in which a separation line is one of the skin-friction lines which originates at a saddle-point of separation. The paper makes it clear that separation in the usual sense of the term may not take place along the whole length of the separation line, but insists that each skin-friction line from which separation takes place can be traced back to its origin at a saddle point. This saddle-point may not be apparent in a particular, necessarily imperfect, experiment or calculation, but it must exist to ensure the topological coherence of the pattern of skin-friction lines (pour assurer la cohérence topologique de l'ensemble). Moreover, the vortical structures must originate near the saddle-point, even though they may be submerged in the boundary layer for some considerable distance, until they are forced away from the wall by streamline convergence to give rise to separation in its usual sense. From this point of view the distinction between open and closed separation made by Wang disappears. Observations and measurements of separated flows in a channel, on the afterbody of ARIANE 5, over a sharp-edged delta wing, in the wake of a blunt-based afterbody, over an ogive-cylinder, and over a round-nosed elliptical cylinder are carefully interpreted in considerable detail in terms of this account. It is agreed that a pattern of skin-friction lines may be consistent with different vortical flow structures and examples are given in which the ambiguity needs to be resolved by measurements within the

fluid. In relation to vortex breakdown, emphasis is placed on its unsteadiness, at least in low-speed flows, and on the importance of the interaction between a vortex and a shock-wave transverse to its axis.

Paper 21. R.C. NELSON, with VISSER, from the University of Notre Dame, Indiana, USA, gave a paper on the role of vorticity in the breakdown of a delta wing vortex. This is based on measurements in a low-speed wind tunnel on the flow over a 75° sweep delta wing at 20 and 30° incidence and over a 70° wing at 20° incidence. All three velocity components are measured using two crossed hot-wire probes on a grid size of 3% local semi-span in a large number of transverse planes. The axial component of vorticity is derived from these. The azimuthal component of vorticity along a traverse through the vortex core is obtained approximately. Vortex breakdown occurs at about mid-chord at 30° incidence. The results are used to show the role of the local semi-span as the relevant length-scale for circulation and vorticity. The distributions of both axial and azimuthal vorticity change abruptly at breakdown and it is suggested that breakdown may be preceded by the occurrence of 'some maximum type of vorticity distribution'. Consideration of the axial velocity distribution leads to the definition of a jet core, and a sub-core is defined in terms of the azimuthal velocity. The axial variations of the diameters of these cores are shown.

Asked about whether the probes influenced breakdown and about the steadiness of the phenomenon, NELSON explained that most data were taken in the healthy vortices and that he was planning to look at the unsteady components of the hot-wire signals.

Paper 22. T.H. LÊ gave a paper on determining criteria for vortex breakdown by solution of the Euler and Navier-Stokes equations with his colleagues MÈGE and MORCHOISNE from ONERA, Chatillon, France. They solve the three-dimensional, time-dependent equations for an incompressible fluid in a rectangular volume with boundary conditions on all six faces. The initial state corresponds to a Batchelor trailing vortex with a velocity along its axis in excess of the ambient value. A Rossby number (Ro) is formed from this axial velocity excess, the circulation, and a vortex radius. A Reynolds number is based on the vortex radius and the ambient axial velocity. A disturbance to the azimuthal velocity is introduced at a point in the vortex core. For a low rate of rotation (high Ro) this does not grow; for a lower Ro it grows, but is convected away downstream; for a lower Ro still it grows upstream and downstream, forming a zone of recirculation. The threshold value of Ro between the last two is regarded as critical for breakdown. This critical value of about 0.62 for Ro is found to be independent of Reynolds number when the latter exceeds 400, and also independent of vortex radius. It relates closely to the conclusions of other calculations and of experiments. Further details are available in earlier publications by the authors.

In response to questions, the speaker explained that a larger initial disturbance would grow faster and that the broken-down flow involved a wide spectrum of frequencies.

Paper 23. J. DELERY presented a paper by PAGAN and MOLTON of ONERA, Chatillon, France, on fundamental studies of vortex breakdown and its control. Experiments and computations which show the effect of blowing along the axis of a vortex are reported. In the experiments, a vortex is generated by a pair of oppositely-deflected winglets mounted on a body of revolution and extending laterally to the tunnel walls. The body extends well downstream of the winglet trailing edges and can be fitted with any of three nozzles which generate axial jets. The vortex is captured downstream between parallel plates fitted with deflectable flaps at their trailing edges, so that a controlled axial pressure gradient can be imposed. The observed positions of breakdown are upstream of this 'air intake'. The velocity field is measured by laser anemometry and tunnel wall pressure distributions are recorded. A substantial data base is generated. Results quoted demonstrate the importance of a Rossby number based on circulation, viscous radius, and axial speed upstream of breakdown. A close relationship is revealed between the ambient pressure gradient and this Rossby number at the initiation of breakdown. Calculations using the Navier-Stokes equations in axisymmetric form yield a very similar relationship, provided the Reynolds number is large enough. The predicted effect of lower Reynolds number is to stabilize the vortex, that is, to allow a lower Rossby number at a particular pressure gradient without breakdown. The measured effect of blowing is also to stabilize the vortex, that is, to displace the location of breakdown in the downstream direction. Close to breakdown the flow becomes turbulent and the laminar calculations no longer predict the axial velocity at all closely.

The discussion which followed established that the Rossby number defined in this paper was regarded as being, in some sense, a universal parameter, although it does differ from that defined in paper 22.

Paper 24. S. AGRAWAL presented an investigation of vortex breakdown on a delta wing using the Euler and Navier-Stokes equations, with BARNETT and ROBINSON, also of the McDonnell Aircraft Co, St Louis, USA. A comparison is made between detailed experimental measurements and computations using a thin-layer Navier-Stokes/Euler code (CFL 3D) for inviscid, laminar, and turbulent flow about a 70° sweep, sharp-edged, flat-plate delta wing at Mach number 0.3, Reynolds number 1 million, and incidences between 25 and 40°. The turbulence model is Baldwin-Lomax, apparently unmodified. The same grids are used for viscous and inviscid calculations: coarse, medium and medium with embedding. They 'are not usually considered fine enough for resolving vortical flows', and results are shown to be grid-sensitive. A striking comparison is of contour plots for the streamwise component of vorticity in cross-flow planes upstream and downstream of breakdown, in which the laminar viscous calculation shows a strong resemblance to the measurements, although the levels are generally too low. The comparison of calculated and observed positions of breakdown as a function of incidence is somewhat disappointing, though the authors report 'the vortex breakdown progression with angle of attack ... was found to be consistent with the experimental data'. Finer grid calculations, perhaps taking account of the wind-tunnel walls, are expected to improve the comparison. The difference between the Euler and Navier-Stokes solutions is principally in the prediction of secondary separation and the associated shift of the primary vortex close to its observed position. The predictions of breakdown position are relatively close, compared with the discrepancy between prediction and observation.

Paper 25. D.M. RAO of Vigyan Inc, Hampton, USA gave an invited paper on vortex management for tailoring configuration aerodynamics. The text was not available at the meeting. Five different management schemes are proposed, aimed at a variety of configurations. For lateral and directional control on a delta wing at high incidence, segmented and differentially deflected leading edge flaps (vortex flaps) are proposed. Benefits are shown from pivoting such flaps ahead of the leading edge, forming a

crude leading-edge slat. For buffet on a twin-tail configuration owing to LEX vortices, two schemes are shown to be effective. A LEX on the tail generates an opposing vortex and reduces the peak level of velocity fluctuations, while a downward deflection of the wing LEX also reduces the level at some cost in lift. The strong interaction between wing leading-edge vortices and vortices generated at the chines of a forebody can be prevented, either by interrupting the chines ahead of the leading edge root or by deflecting downwards an inboard, partial-span, leading edge flap. The chine vortices themselves can be controlled in symmetric and asymmetric modes either by chine deflection, up or down, or by spanwise blowing from the chines. The post-stall behaviour of high-aspect-ratio unswept wings can be modified to increase resistance to departure by cutting slots into the leading edge to generate vortex pairs over the wing.

In response to questions it emerged that such slots caused less drag than vortex generators and that the dorsal tail extension operated by distorting the vortex field. Comments were made on the need to consider time-lag effects in the use of forebody controls and the effects of Reynolds number and dynamics on configurations with dorsal fin extensions.

Paper 26. R. STAUFENBIEL presented an invited paper on aircraft wake properties and some methods for stimulating the breakdown and decay of tip vortices, by himself and VITTING, from the University of Technology, Aachen, Germany. The text was not available at the meeting. The first part of the paper describes calculations of wake roll-up using the analogy to two-dimensional time-dependent flow. The vortex sheet is discretized using point vortices, which are amalgamated into a core with a Lamb-Oseen structure to prevent the sheet intersecting itself. The amalgamation process conserves the most significant parameters of the wake. The results agree with laser-Doppler anemometer measurements in a water-tunnel in showing an increase in core radius, a slow reduction in circumferential velocity, and a reduction in axial velocity, in the downstream direction. The second part of the paper describes several methods for reducing vortex strength, applied to unswept wings of high aspect ratio. Calculations show a marked influence of the spanwise lift distribution on the maximum tangential velocity and a much reduced value is measured behind a wing with an ogival tip. A wing-tip spoiler is shown to be relatively ineffective. A half-delta tip generates a leading-edge vortex which breaks down upstream of the trailing edge, giving a useful reduction in maximum tangential velocity. A particularly promising device is a four-vaned static splitter trailed in the tip vortex. This spreads the vortex, reduces the maximum tangential velocity by two-thirds, and leads to a small reduction in overall drag.

In response to questions, the speaker agreed that the static splitter could be replaced by a rotor, thereby extracting power, but losing the drag reduction. If the surface area and weight of the splitter were used to extend the wing span, drag would be reduced, but the peak tangential velocity would not be reduced.

Paper 27. A.J. ROSS gave a paper on the control of forebody vortices by suction at the nose of the RAE high-incidence research model, by herself, JEFFERIES and EDWARDS of RAE, Farnborough, UK. The configuration has canard, wing, horizontal tail and single fin surfaces, and a short, drooped forebody. It is tested statically and dynamically in a low-speed tunnel in this form and with a longer, undrooped forebody. Suction is applied at two small orifices on the upper side of the forebodies, very near the nose. Control power is found to depend on mass flow rather than momentum flow, and is closely proportional to flow rate, up to a saturation level. This level depends on the side force generated by the forebody in the absence of suction, so that it increases with incidence, and is much larger for the longer forebody. At an incidence of 30°, suction on this forebody gives a yawing moment equivalent to 25° of rudder deflection, and significantly more at higher angles of incidence. Its effectiveness is somewhat reduced by transition fixing. Results of tests on a free-to-yaw rig with active control of flow rate are described. The next stages in the research programme are outlined.

Questioners commented on the low flow rate required, suggested combining suction on one side with blowing on the other, and asked why transition fixing reduced effectiveness. ROSS replied that the low flow rate is associated with the far forward location of the orifices and that blowing is unlikely to have any further effect because the flow appears to be in an extreme state already. Presumably transition fixing reduces the side-force attained in the absence of suction.

Paper 28. D.A. LOVELL of RAE, Farnborough, UK gave a paper on an experimental investigation of vortex flaps on a canard combat-aircraft configuration. Forces and moments are measured in a low-speed tunnel on a configuration with a cambered wing of 53° sweep mounted low on a fuselage of rectangular cross-section, with a close-coupled canard mounted high. Some wing oil-flow pictures are shown. The vortex flaps are thin, full-span surfaces, mounted on the wing lower surface 5% chord aft of the leading edge. Constant-chord and constant-percentage-chord versions of three different sizes are used. Lift and drag values are shown for a wide variety of configurations at incidences up to 47°, a chord Reynolds number of 2 million, and transition fixed on the fuselage. The main conclusions are: at moderate angles of incidence the vortex flap is as good as a conventional drooped leading edge, at high lift coefficients the vortex flaps are much better than a 10° drooped leading edge, a constant-chord flap is better than a tapered flap, the performance obtained with vortex-flap configurations is very sensitive to canard angle, and trailing edge flaps remain effective up to the largest test incidence when used in conjunction with vortex flaps. With pitching moment characteristics taken into account, it is shown that vortex flaps offer greatly enhanced manoeuvrability for canard configurations.

A comment was made that MBB studies had found problems with lateral characteristics on vortex-flap configurations which they had not managed to cure. It was confirmed that the RAE tests do cover all six components.

Paper 29. A.M. CUNNINGHAM Jnr of General Dynamics, Fort Worth, Texas, USA presented a paper on the steady and unsteady aerodynamics of a pitching straked wing model at high angles of attack with DEN BOER of NLR, the Netherlands. This is the latest in a sequence reporting and analysing low-speed wind-tunnel tests carried out at NLR in 1986 on a cropped double-delta wing of 76/40° leading edge sweep. It presents force and moment data from pitch oscillations at amplitudes up to 36° peak-to-peak at frequencies up to 16 Hz in symmetric flow and with 5° of yaw, subject to a maximum instantaneous incidence of 50°. Particular relevance is seen to the 'Cobra' manoeuvre of the Su-27. Results are interpreted in terms of regimes of linear flow, vortex flow, burst vortex flow, and fully-separated flow, as observed in steady symmetric flow at increasing incidence. Under yawed conditions extra regimes appear as a result of the simultaneous occurrence of different basic regimes on the two wing panels. Successive pairs of

regimes are separated by transition points. Hysteresis in unsteady flow is more significant when higher incidences are involved, at higher frequencies, and when transition points lie in the pitch excursion. Striking effects of frequency and amplitude are seen in both symmetric and asymmetric flow. Serious consequences are seen for modelling aircraft flight-paths in post-stall manoeuvring, since forces and moments depend not only on instantaneous values of the state variables, but also on the history of the motion. In specific terms, it matters whether or not one of the vortices suffered break-down over the wing in the recent past.

A comment was made suggesting that unsteady effects could be seen in terms of three time-constants relating to vortex convection, breakdown and total stall.

Paper 30. D. BROWN presented a paper on some characteristics and effects of the F/A-18 LEX vortices, with colleagues LEE and TANG from the Institute for Aerospace Research (formerly NAE), Ottawa, Canada. Tests of a 6% scale, rigid model of the configuration at Mach numbers from 0.2 to 0.8 and angles of incidence up to 35° are described. They are carried out with and without the LEX fences which have been shown in flight tests to reduce the acceleration of the fin tip from 450 to 200 g. Steady pressures are measured along two lines on the forebody and along two lines on the LEX. Unsteady pressures are measured at 4 points on the LEX and at 24 points on each side of a fin. The wake region behind the fin is surveyed with a fixed rake of 45 total-pressure tubes, 13 of which measure unsteady pressure. With the fence in place, the level of unsteady pressure measured on the fin at 30° incidence is reduced at all Mach numbers, with the larger reduction on the inboard surface of the fin. The cross-correlations between the unsteady pressure signals on the fin are consistent with disturbances moving in the direction of the local flow at speeds below free-stream speed. Contours of time-averaged total pressure in the wake show differences due to the presence of the fence, and it is suggested that a vortex shed from the fence can be identified.

In response to a question it was suggested that the fence acts as a vortex generator, with the additional vortex acting to displace the LEX vortex.

Paper 31. E.S. HANFF, of IAR, Ottawa, Canada gave a paper on multiple roll attractors of a delta wing at high incidence, with ERICSSON of Lockheed, Sunnyvale, USA. The motion of a delta wing with 65° sweep at an incidence of 30°, rolling about its centreline, in a low-speed tunnel, is considered. The rolling moment is measured in static conditions and in forced oscillations of various amplitudes, at various frequencies, and about various mean roll angles. These data are used to present rolling moment as a function of roll angle and roll rate for various mean roll angles. Histories of roll angle development from free-to-roll tests are recorded for release from rest at various initial angles. These show convergence to stable trim points at angles of zero and ±21°, the multiple roll attractors. The static, and some of the dynamic, tests show zero rolling moment for zero roll rate at these roll angles. It is shown that two of the histories of roll angle development, each of which involves several passages through the attractors, can be predicted successfully using the dynamic data. The way in which other histories escape from attractors at which the roll rate is instantaneously zero is explained in qualitative terms. It is suggested that the movement of vortex breakdown over the two halves of the wing as the effective sweep and incidence change with roll angle is an important element in generating these striking phenomena.

CUNNINGHAM commented that he found (paper 29) that oscillatory and transient forces are similar if the flow is in the same state. HANFF agreed that there had to be some length of similar history. ERICSSON added that when the rate of change is higher a longer length of similar history is required. In response to questions it emerged that the analysis in terms of harmonics of the motion frequency had effectively suppressed tendencies to chaos and that publication of the flow field visualizations hinged on the availability of a PhD student.

Paper 32. C.R. KAYKAYOGLU presented a paper on a numerical simulation of the interaction between a vortex street and a plate, prepared with colleagues KAYA and BAYAR from the Istanbul Technical University, Turkey, and GRAHAM from Imperial College, London, UK. The flow is incompressible and the vortex street is generated by separation from the sharp corners of the blunt base of an upstream plate. Three different downstream plates, with sharp, rounded, and blunt leading edges, are considered, each aligned with the upstream plate and the ambient flow. The gap is about six plate thicknesses. Two computational schemes for two-dimensional flow are used, one inviscid, and the other viscous, at a Reynolds number of 1800 based on plate thickness. Both schemes use conformal mappings to simplify the computational space, enabling image vorticity to be used to satisfy boundary conditions, and allowing simple grid generation. The inviscid scheme is a developed form of the discrete vortex model. The viscous scheme, apparently novel, combines a Lagrangian representation of vorticity convection with an Eulerian representation of vorticity diffusion in a two-step approach. Results are presented for the Lagrangian representation of the vorticity, for instantaneous streamlines and velocity vectors, for contours of the Eulerian representation of the vorticity, and for the time variation of the pressure on the downstream plate. This is believed to be the first calculation to take account of the upstream effect of the plate on the formation of the street. Agreement is found with previously published flow visualizations.

Responses to questions established that the boundary layer on the upstream plate is only simulated in the viscous method, and that separation on the downstream plate only occurs at sharp corners.

Paper 33. A. BARON gave a paper on a numerical simulation of vortex flows past impulsively-started wings, with colleagues BOFFADOSSI and DE PONTE from the Polytechnic of Milan, Italy. The method, applied to wings without thickness, alone and in combination, is basically a vortex lattice method for incompressible flow. The lattice is extended into the fluid at all edges from which separation is postulated to occur. In the fluid the vortex filaments are given a notional radius, which serves as a cut-off distance preventing the calculation of unbounded convective velocities. This radius is derived in a rational way from an empirical expression for the growth rate of a turbulent shear layer. Results are found to be relatively insensitive to the number of vortices used in the discretization. No estimate of an initial vortex configuration is needed because all calculations start from rest. A sufficiently close approximation to a steady state over the wing is found after it has travelled about six chords. Results are shown for rectangular wings with aspect ratios 6 and 1, with separation from side and trailing edges, for a delta wing of unit aspect ratio at an incidence of 20.5° with separation from all edges, and for a wing-canard combination of cropped-delta wings with separation from tips and trailing edges. For the low aspect ratio cases, satisfactory agreement was obtained with steady state measurements.

In response to a number of questions, the speaker thought periodic flows could be calculated, though this had not been attempted. He preferred not to attempt to reproduce the flows described by OELKER (paper 14). He agreed the roll-up of the starting vortex is rather weak, attributing this to a coarse discretization. It is not easy to refine the discretization, so the method is mainly useful in the preliminary design stage. If an attempt were to be made to model a dead-water region using two vortex sheets, he saw difficulties in applying an appropriate Kutta condition.

4 CONTRIBUTIONS TO KEY ISSUES

In this section an attempt is made to set the contributions made by the papers and the discussion in the context of a number of key issues. Since these issues overlap, some repetition is inevitable.

4.1 Computation of wing flows

Hoeijmakers[1] gave a comprehensive survey of computational techniques available, with examples, listing strengths and weaknesses. Most of the other computational papers are concerned with solutions of the Euler equations[3-5], the Navier-Stokes equations[7,9,11], or both[2,8,22-24]; and Hoeijmakers' comments[1] on these methods are relevant. The papers by Riley[10] and Baron[33] present significant variants on the schemes discussed by Hoeijmakers. Riley combines a vortex-sheet model of the primary leading-edge vortex with a laminar boundary layer model of the secondary separation. This clarifies the flow mechanisms involved, but is unlikely to lead to a general predictive method. Baron[33] does present a general predictive method for low-speed flows in which the separation lines are known, using vortex sheets embedded in potential flow, and avoiding the need for a good initial guess at the vortex configuration by calculating the development from an impulsive start. Such an approach usually involves shedding a large number of vortex elements, often leading to chaos rather than a steady state, but Baron claims his discretization needs fewer elements and approaches a steady state quickly.

A major theme of the meeting was the comparison between solutions of the Euler and the Navier-Stokes equations. The detailed information presented in the papers will help the user decide whether the extra cost of a Navier-Stokes solution is justified for his purposes. For wings with round leading edges Euler solvers do not predict the origin of the leading-edge vortex in a reliable fashion. Indeed, many believe that if a sufficiently fine grid were used, an Euler code would predict attached flow at a round edge. Separation could be fixed, along all or part of the edge, by applying some form of Kutta condition, but no examples of such calculations were shown at the meeting. For a sharp-edged wing, Euler solvers predict leading-edge vortices consistently, but secondary separation is not predicted, so the wing pressure distribution cannot be predicted accurately without an imposed Kutta condition. Use of the Navier-Stokes equations allows the prediction of primary and secondary separation from round and sharp leading edges in laminar and turbulent flow. So far, the detailed pressure distribution between the secondary separation line and the leading edge is not reliably predicted and it is not clear whether inadequate grids or inadequate turbulence models are to blame.

The emphasis on the comparison between Euler and Navier-Stokes solutions tends to conceal their common strengths and weaknesses. Both yield estimates of vortex breakdown position which bear comparison with observation[24]. Both describe the formation of shock waves above the wing at transonic speeds: shocks parallel to the vortices, lying between them and the wing surface, and shocks normal to the wing centre line. Accurate prediction of separation with the Navier-Stokes equations requires supplementary information about the state of the boundary layers approaching the separation lines. The results of both Euler and Navier-Stokes calculations are still dependent on grid size, even with the finest grids used. More elaborate turbulence models would be needed to represent the turbulence in the free shear layers and vortex cores.

Generating grids for the accurate calculation of vortex flow is difficult. The little that is known mathematically about the structure of vortex cores suggests that extremely small length scales are involved. Experimental resolution of vortex cores is difficult, but there is evidence of a viscous sub-core on a smaller scale than the rotational core. It may be, however, that detailed resolution of the core structure is unnecessary. There is much evidence of this for the prediction of wing properties in the absence of breakdown. It remains to be seen whether an accurate representation of the core structure is needed to predict the breakdown of wing vortices and their interaction with other aerodynamic surfaces. What is certain is that grids which are finer over the vortices than those currently used will be needed. Authors already using multi-block and embedded grids for their calculations suggest that efficient calculation of vortex flows will require adaptive grids. For structured grids, adaptation is a complicated process, even for flows which are predominantly two-dimensional and for which the dominant structures, a shock wave and a boundary layer, are approximately aligned with the grid. This suggests the use of unstructured grids[3], which can be refined locally as required. However, three-dimensional unstructured grids are very hard to inspect visually, and no completely convincing substitute for visual inspection of grid quality is yet available.

The algorithms in use for both the Euler and Navier-Stokes equations for compressible flow have been derived with the aim of capturing shock waves accurately and efficiently. They do not capture shear layers so well. This is essentially because there is no physical process which counteracts the diffusive processes of physical and artificial viscosity, in the way that the physical steepening of compression waves acts to sharpen shocks. Paper 32, for two-dimensional incompressible flows, presented an approach in which the convection and diffusion of vorticity are treated in separate steps, with convection treated in a non-diffusive, Lagrangian representation. It is not clear whether this approach can be extended either to three-dimensional or to compressible flow.

4.2 Vortex breakdown

It seems to be generally agreed that vortex breakdown is not understood, though a great deal is known about the parameters which affect it and about the effects it produces on aerodynamic characteristics. The meeting produced further evidence that the breakdown mechanism is essentially inviscid, at least at Reynolds numbers relevant to aircraft flight. This came in papers by LÊ[22] and PAGAN[23] which established the upper limit of Reynolds number beyond which Navier-Stokes and Euler calculations agree in their prediction of breakdown in isolated vortices. Also, Euler calculations by AGRAWAL[24] show the breakdown of wing vortices reasonably close to its observed position. The wing vortex which emerges from an Euler calculation is not, of course, the same as that given by a Navier-Stokes calculation, because secondary separation is not represented, so discrepancies of detail must be

expected in the prediction of breakdown over wings. Indeed HOUTMAN[5] showed Euler calculations which gave no indication of breakdown in a wing flow for which it had been observed.

The ambitious programme set out by AGRAWAL[24], involving detailed flow-field measurements and calculations for delta-wing flows has been only partially successful so far. The inviscid and viscous predictions for the variation of breakdown position with incidence differ, as we should expect, but both also differ from observation. Further assessment must await the planned calculations on finer grids, and it may be necessary to represent the tunnel walls in the calculation. At present the calculations fail to predict the detailed velocity profiles measured in the vortex core. The calculations by PAGAN[23] suggest that such profile differences do affect the location of breakdown, but it is not clear in general how close a representation of the flow in the core is required for an accurate prediction of breakdown.

The effects of breakdown on aerodynamic characteristics are known to be significant in three respects. First, the displacement effect of the enlarged core downstream of breakdown has a direct effect on lift, pitching moment and, in asymmetric flow, rolling moment, starting from the incidence at which breakdown reaches the trailing edge. It also has a dramatic effect at transonic speeds in accelerating the flow behind a forward transverse shock to locally supersonic speed, so that a rearward transverse shock is needed to return to free-stream conditions, as shown by HOUTMAN[5] and ELSENAAR[15]. Secondly, the maximum circumferential velocity in the vortex is much reduced after breakdown, an effect which can be exploited in reducing the trailing vortex hazard to following aircraft, as described by STAUFENBIEL[26]. Thirdly, the level of pressure fluctuations is very much increased downstream of breakdown, so that a broken-down vortex presents a dangerous environment for a tail surface, as discussed by MABEY[12], DEL FRATE[13] and BROWN[30]. A new effect was described by OELKER[14] at the meeting. When, with an increase of incidence or side-slip, vortex breakdown reaches the apex of the wing panel, the flow over that panel stalls completely, with the formation of a dead-water region. CUNNINGHAM[29] described something similar. Whereas the changes in aerodynamic derivatives that come about from the gradual advance of breakdown over the wing are themselves gradual, sudden changes arise when the dead-water region forms. Moreover, on a wing-canard configuration tested in a water-tunnel, a bubble of fluid was formed which persisted over a substantial period of time, possible introducing a long time scale into a dynamic situation. It is important to know whether a similar effect occurs at higher Reynolds numbers, in turbulent conditions. The movement of vortex breakdown fore and aft over the wing, including the stall that is associated with its reaching the apex, plays a large part in the account of hysteresis in forces and moments on a pitching wing which is given by CUNNINGHAM[29].

4.3 Unsteady flows

Unsteady flows fall into two groups, those for which body motion is an essential part of the mechanism and those for which an intrinsic unsteadiness exists in the flow and may excite a response from the body. An under-current running through the meeting concerned whether the tail motion on the F18, as displayed by DEL FRATE[13], fell into the first or the second group. Many participants felt that this large-scale motion, and the sharp peak in the spectrum of unsteady pressures shown by MABEY[12], implied some degree of positive feed-back between the motion and the unsteady pressure field. However, in the general discussion session MABEY was very firm that the levels of unsteady pressure measured on a rigid model are adequate to explain the excitation of the observed oscillation. This view is supported by BROWN'S[30] measurements of unsteady pressures on and near the tail of a rigid model. These showed that the fences which reduced the motion on the aircraft in flight also reduced the pressure fluctuations on the model. Unfortunately, even these detailed measurements were not sufficient to produce a completely convincing account of the mechanism.

An important element in understanding the flow mechanism is to know whether the pressure fluctuations observed at a point arise from the motion through the point of the pressure field associated with a large coherent structure, such as a vortex, or whether the fluctuations arise from unsteadiness within an almost stationary feature. Measurements of unsteady pressures do not always resolve the question. KAYA[32] illustrated a further complexity, showing that the profile of the leading edge of a plate placed in the wake of an upstream blunt-based plate affected the frequency of the vortex street being shed into the wake.

The papers by CUNNINGHAM[29] and HANFF[31] were both concerned with large, rapid wing motions, in pitch and roll respectively. These motions involve large angles of effective incidence and the movement of vortex breakdown fore and aft. The authors take rather different attitudes to the interpretation of their results and consequently to the use of their results in a predictive scheme. HANFF hopes that the forces and moments acting in such extreme manoeuvres can be characterized adequately by instantaneous values of the state and motion parameters, in his case roll angle, roll rate and perhaps roll acceleration. The dependence could then be determined in forced oscillations, using various amplitudes, frequencies and mean values. CUNNINGHAM, on the other hand, regards the whole history of the motion as potentially relevant, paying particular attention to any transitions between the regimes of attached flow, vortex flow, flow with breakdown over the wing, and fully stalled flow. These transitions are seen as introducing bifurcations into the dependence of forces and moments on state and motion parameters. It was not claimed that either approach would necessarily be adequate, and it may be that, in sensitive cases, a time-accurate solution of the Navier-Stokes equations along the flight path will be required.

It is tempting to think that, since such extreme flight paths are likely to be traversed at low speeds and with separation from all edges, the forces and moments required might be obtainable from a relatively simple inviscid incompressible calculation, such as that proposed by BARON[33]. Substantial development of that method would be required, so, before undertaking a task of such magnitude, it would be desirable to re-examine other techniques, such as the vortex element technique devised at ONERA by REHBACH. This has the advantage of not requiring the vortex elements to be connected in any orderly structure, allowing the simulation of vortex breakdown.

4.4 Asymmetric body vortices

The formation of asymmetric body vortices and the side-force and yawing moment they produce is the area where understanding and predictive capability are most limited. The discovery over the last 10 years that various models of separated vortex flow over circular and elliptic cones posses asymmetric as well as symmetric solutions seemed a substantial step forward. PIDD[18] took a further step along this path by demonstrating that, for the simplest

model, stability considerations eliminated the symmetric solutions at the larger incidences. The need to tread other paths was shown by his presentation of a variety of highly non-conical, substantially asymmetric, low-speed flows over circular cones, as well as by ROSS's[27] demonstration that suction near the nose of a fore-body at high incidence can produce a side force and yawing moment proportional to flow rate. Asymmetry is produced towards the rear of cylindrical bodies at angles of incidence below that at which any asymmetry is perceptible at the nose. MOIR[19] showed evidence that even in these circumstances the direction of the side force is determined by the roll attitude of the fore-body rather than that of the afterbody.

Whereas 10 years ago it seemed that flows about bodies with pointed noses might be easier to understand than flows about bodies with round noses, using slender-body theory and conical similarity, it now seems that the reverse might be the case. The calculation of a reliable numerical solution of the Navier-Stokes equations for laminar flow over a round-nosed body is now practicable, and the effects of small geometrical asymmetries should be calculable. Because of the vanishingly small local scale involved, it may be doubted whether a numerical solution for a pointed body in subsonic flow can ever be accurate near the nose.

4.5 Separation and (re)-attachment in three-dimensional flow

HOEIJMAKERS[1] and RILEY[10] agreed that secondary separation on a delta wing could be calculated by an inviscid model of the outer flow with a boundary layer model of the inner flow. They also agreed that the calculation must be interactive, and the interaction must be in some sense simultaneous. It appears from their solutions that, at least for Reynolds numbers for which secondary separation is laminar, the wing pressure distribution is better predicted if the inviscid model of the secondary vortex comprises simply the displacement effect of the boundary layer than if an explicit vortex-sheet model of the secondary vortex is introduced. The behaviour of a real flow, even at wind-tunnel Reynolds numbers, is complicated by the occurrence of transition in the separated shear layer, even though the upstream boundary layer is laminar.

Both DALLMAN[9] and DELERY[20] discussed the patterns of skin-friction lines which are made visible by surface oil-flow in experiments and can now be simulated in computations. These are universally regarded as valuable indications of where the flow is leaving the surface, carrying fluid with rotation and reduced total pressure from the wall into the body of the fluid; and of where the flow is approaching the surface, thinning and stabilizing the boundary layer. These locations are called 'separation lines' and 'attachment lines'. The importance of these lines or narrow regions, both for understanding and modifying vortex flows and for constructing inviscid models of them, has led to determined efforts to characterize them by some qualitative property. DELERY[20] reiterated, with some important qualifications, the classical account given by Legendre and Lighthill, in which every separation line originates at a saddle-point of the pattern of skin-friction lines. DALLMAN[9] showed examples in which separation originates at an ordinary point of the pattern of skin-friction lines, the 'open separation' of WANG. DELERY[20] reconciles these observations with the classical account in the following way. The skin-friction line from which separation is seen to take place is followed back upstream until a critical point is reached, and the whole of the line is called a separation line, even though separation is only taking place from the downstream part of it. If the critical point that is reached appears to be a node, it is supposed that there is a neighbouring saddle point and a further node very close to the node that is seen, so close that they cannot be resolved by the experimental or computational technique which is in use. The separation line then runs into the saddle point. Some embryonic vortical structure, buried within the boundary layer, is postulated to connect the saddle point with the vortex which subsequently separates further downstream. This extension of the classical approach to embrace open separation seems to preserve the formulation at the expense of the physical content. In practice it seems that the strong convergence of the skin-friction lines which indicates separation to the observer is encouraged by the vortex which emerges from the separation line, so that a model representing both the boundary layer and the vortex is needed to provide a convincing account of the process.

If we suppose that steady, two-dimensional or axi-symmetric, separation bubbles exist, then the streamline which leaves the surface at separation returns to the surface further downstream to close the bubble, and we can say the flow reattaches. In the flow over a highly-swept delta wing at a large incidence, the stream surface which impinges on the upper surface of the wing is quite clear of the leading-edge vortex. It brings fluid particles with zero vorticity, and with free-stream total pressure, into the upper surface boundary layer. We should say the flow attaches, rather than reattaches. On less highly swept delta wings at smaller angles of incidence, the stream surface which impinges on the upper surface is still distinct from the stream surface which separates from the leading edge. However, cross-stream laminar diffusion at low Reynolds number or turbulent mixing at high Reynolds number may impart rotation to, and lower the total pressure of, the fluid particles which impinge on the wing surface. The impinging flow may even be turbulent. This implies a whole range of states intermediate between those initially characterised as reattaching and attaching. The case studied by PAILHAS[16] falls somewhere in this range. It would be useful to extend his work to explore the range more fully.

It is well known that existing turbulence models are more or less unsatisfactory for separating flows in two dimensions, perhaps because large-scale, low-frequency motions appear. In highly three-dimensional separated flows such motions are absent or less significant and simple turbulence models have a better change of succeeding. Calculations reported by KAYNAK[11] showed that simple local turbulence models did as well in predicting three-dimensional separations as a more elaborate model which takes account of upstream evolution. Whatever the eventual explanation, this is good news for those calculating flow separation on combat aircraft and weapons, where it is usually significantly three-dimensional.

4.6 Vortex exploitation and control

Apart from the four papers presented in session VI under this heading, two others deserve consideration in the same context. The study by PAGAN[23] is clearly related to the possibility of delaying vortex breakdown by blowing along the axis of the vortex. He finds significant effects of the fluxes of mass and momentum, but no consideration is given to any flight application. BROWN[30] suggests that the LEX fence on the F18, instrumental in alleviating tail buffeting, operates by generating a further vortex which displaces the LEX vortex far enough to produce the alleviation. STAUFENBIEL[26], like PAGAN, is concerned with control of vortex structure, but he welcomes and encourages the breakdown of wing-tip vortices in the interests of reducing the peak circumferential velocities

they induce. In addition to a tip in the form of half a delta wing, which leads to breakdown ahead of the trailing edge, he shows an ogival wing tip which spreads the circulation over more of the wing semi-span, and a static vane which spreads the circulation of a tightly rolled tip vortex over a much larger area downstream. These devices are shown to be effective in reducing peak velocities at downstream distances comparable with the wing dimensions, so that they would reduce the intensity of blade-vortex interaction on helicopters. It is not easy to assess either experimentally or theoretically how effective they are at distances like the separation between landing aircraft.

Lateral control of an aircraft at high incidence is difficult, with fin and rudder immersed in the wing wake and the wing tips stalled. Otherwise it is unlikely that anyone would try to use the little-understood vortex asymmetry on forebodies to generate yawing moment in a controlled way. Proposals to influence the vortex asymmetry by blowing from the nose are familiar, however, and ROSS[27] shows that, given a long pointed forebody, large yawing moments can be produced with low mass-flow rates if suction is applied at lateral orifices on the upper side of the forebody, very close to the nose. Moreover, up to a maximum level fixed by the naturally occurring asymmetry, the yawing moment produced is proportional to the mass flow. She shows how these yawing moments can be applied to control the attitude of a model on a free-to-yaw ring.

LOVELL[28] demonstrates the capabilities of leading-edge vortex flaps, deflected downwards and used in conjunction with trailing-edge flaps, to generate significant improvements in trimmed lift-to-drag ratio at large lift coefficients on a canard-wing configuration. The conventional explanation for the aerodynamic efficiency of vortex flaps is that the leading-edge vortex is trapped over the forward-facing surface of the flap. However, LOVELL finds that the maximum thrust is produced when the vortex spills over on the upper surface of the wing at about mid-semi-span, so even in this relatively well understood area our understanding is incomplete. RAO[25] describes several developments of the basic vortex flap, among a number of schemes for controlling separated flows, and presents evidence of their effectiveness. Some of these devices, like the chines which fix the origin of separation on a forebody and the slots cut in the leading edge of an unswept wing of high aspect ratio, act to increase the stability and predictability of the flow field. Others, like part-span leading-edge flaps and a fin LEX, act by increasing the number of distinct vortices which stream back over the configuration. The first group tend to reduce the requirement for wind-tunnel testing (or computation) and any residual uncertainty about flight behaviour. The second group, although effective in relation to their design aims, may increase the need for testing, and perhaps the residual uncertainty.

4.7 Techniques

MABEY[12] stressed the importance of the state of the boundary layer in studies of separated flow, recommending that transition be fixed in all experiments. The most obvious benefit of transition fixing is that an important source of variability in measurements and observations is eliminated. The expected benefit is the reduction, or, more optimistically, the elimination, of scale effect, so that tunnel tests at low Reynolds numbers more closely resemble flight conditions at high Reynolds number. However it must be remembered that the turbulent boundary layer downstream of a transition trip differs from a naturally turbulent boundary layer for a considerable distance downstream of the trip, the difference being greatest nearest to the trip and the greater the larger the trip. There are also circumstance in which the extent of the boundary layer that is laminar even at flight Reynolds numbers is large enough to be significant, such as body vortex flows. We should therefore be seeking the minimum size of trip that will ensure transition, placed close to the location of free transition at full-scale, though even more elaborate techniques, aimed at reproducing the full-scale boundary layer thickness at a shock location, are used in aerofoil tests. Each boundary layer springing from each attachment line needs to be considered, though only those subject to separation may need to be tripped. Even when the flow is steady and its structure is familiar, proper transition fixing requires either an extensive *ad hoc* investigation or a stock of relevant expertise. Further investigation is needed if the flow structure is not known. If the flow is unsteady on a large scale, it may be impossible to reproduce artificially at a low Reynolds number. This is not to argue that transition fixing should be abandoned, but that we need to be aware of the complexities involved and the limitations of the crude approaches on which we usually have to rely.

One of the difficulties of vortex modelling has arisen from the problems of making measurements within the vortex core. Probes are liable to shift the vortex or provoke breakdown, and their calibration in rotational flow with total pressure gradients in uncertain. Laser Doppler anemometry avoids these problems, but usually relies on flow seeding, which is difficult in cores. Even when it works it only provides information on velocity. AGRAWAL[24] provided a glimpse of an extensive data base including probe and LDA measurements, including LDA measurements on a traverse through the vortex axis. This may help to validate probe measurements as well as providing a valuable source of information. CFD techniques should now be capable of predicting the behaviour of probes in non-uniform flows, so that reliable probe measurements of pressure can complement LDA measurements of velocity.

The surface oil-flow visualizations in flight described by DEL FRATE[13] represent an advance. Oil was released with the aircraft in the desired attitude, at the desired speed, and these conditions were maintained until the oil had dried out. The trace could then be examined and photographed from all angles at leisure on the ground, in the knowledge that every feature had been generated under the desired conditions.

HOEIJMAKERS[1] emphasized how essential computer-based techniques for handling the vast quantities of data produced by CFD have now become. In particular, the transfer of values of pressure, velocity etc from the points where they are calculated to points at which they are required for display or comparison with experimental or other computational data requires interpolation, and sometimes extrapolation, in three-dimensional spaced. Evaluation of vorticity requires numerical differentiation of velocity data. Contour plotting involves decision-making routines. Streamline tracing needs care if solid surfaces are not to be traversed. Calculating skin-friction lines needs extrapolation or numerical differentiation. Methods used for these processes depend on whether grids are structured or unstructured. We need to be aware of these difficulties to appreciate the resources and resourcefulness needed to overcome them and to be able to ask the right questions.

5 CONCLUSIONS AND RECOMMENDATIONS

(a) The range of topics proposed was covered in a variety of papers of great interest and high technical standard, from

which useful discussions developed. The meeting met its declared aims.

(b) Vortex flows retain their importance and their fascination.

(c) Progress in the computation of vortex flow has continued.

(d) Inviscid flow-field calculation (Euler) methods provide insight into compressible vortex flows, including shock-wave interactions, and predictive capability where the origin of separation is fixed at sharp edges.

(e) Viscous and turbulent flow field calculation (Navier-Stokes and Reynolds-averaged Navier-Stokes) methods will take over from inviscid methods wherever increased accuracy makes the extra cost acceptable.

(f) There are indications that highly three-dimensional flow separation is less sensitive to the turbulence model used than nearly two-dimensional separation.

(g) Calculation of the flow near the axis of a wing vortex remains unsatisfactory.

(h) The development of schemes of grid adaptation for vortex flows is key area of work.

(i) It is not clear whether the breakdown of a wing vortex can be predicted adequately without a much better representation of flow in the vortex core.

(j) Asymmetric body vortices continue to surprise, both when they originate at a pointed nose and when they first appear further aft.

(k) Rapid manoeuvres to high effective angles of incidence involve significant hysteresis in forces and moments, associated with changes in flow structure. It is not clear that flight path modelling based on forces and moments measured in a limited range of motions can be successful. Attention should be given to the time-accurate solution of the Reynolds-averaged Navier-Stokes equations as an alternative approach.

(l) The mechanism of three-dimensional separation by which a thickening boundary layer gives birth to a vortex from a smoothly-curved surface is still not fully understood.

(m) The sensitivity of vortex flows to the state of the separating boundary layer is important and not easily reproduced in model tests or calculations.

(n) Measurements of flow in vortex cores are still open to question.

(o) Much can be done to exploit, influence and control vortex flows, but the mechanisms involved at not always clear and computation has scarcely begun to contribute to this ability.

(p) The development of post-processing techniques for the analysis, comparison and display of flow-field information is of continuing importance. This can only grow as the requirement to reproduce time-dependent flows increases.

(q) It would be advantageous if meeting participants were provided with pre-prints or summaries of papers to be presented in advance of the meeting.

(r) Efforts should be made to ensure that written versions of papers are available at the meeting.

(s) Consideration should be given to re-issuing advice to authors on standards for the preparation of visual aids.

(t) Consideration should be given to whether re-timing of the Fall Meeting might facilitate the attendance of NASA staff.

Appendix A

PROGRAMME COMMITTEE

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Appendix B

LIST OF PAPERS

Sessions I and II – VORTEX COMPUTATIONAL TECHNIQUES

1 H.W.M. HOEIJMAKERS
'Modelling and Numerical Simulation of Vortex Flows in Aerodynamics'

2 B.R. WILLIAMS, W. KORDULLA, M. BORSI, H.W.M. HOEIJMAKERS
'Comparison of Solutions of Various Euler Solvers and one Navier-Stokes Solver for the Flow about a Sharp-edged Cropped Delta wing'

3 V. SELMIN, L. FORMAGGIA, N. CERESOLA, M. BORSI
'Vortical Flow Simulation by Using Structured and Unstructured Grids'

4 J.M.J.W. JACOBS, J.I. van den BERG, H.W.M. HOEIJMAKERS
'Analysis of Results of an Euler-Equation Method Applied to Leading-Edge Vortex Flow'

5 W.J. BANNINK, E.M. HOUTMAN
'Experimental and Numerical Investigation of the Vortex Flow over a Delta Wing at Transonic Speed'

The invited paper No.6, J.M. LUCKRING 'Review of Vortex Computational Techniques', was not presented, but is included in the Conference Proceedings, AGARD-CP-494

7 A. HILGENSTOCK, H. VOLMERS
'On the Simulation of Compressible Turbulent Flows past Delta Wing and Delta-Wing-Body Combinations'

8 E.M. MURMAN, A. RIZZI
'Calculation of Hypersonic Leeside Vortices over Blunt Delta Wings'

9 U. DALLMANN, A. HILGENSTOCK, S. REIDELBAUCH, B. SCHULTE-WERNING
'On the Footprints of Three-Dimensional Vortex Flows about Blunt Bodies'

10 N. RILEY, K. KIRKKOPRU
'Secondary Separation on a Slender Wing'

11 U. KAYNAK, M. DINDAR, R. BARLAS
'Non-equilibrium Turbulence-modelling Effects on Transonic Vortical Flows about Delta Wings'

Session III – MEASUREMENTS AND VISUALIZATION

12 D.G. MABEY
'Aircraft Loads due to Flow Separation'

13 J.H. DEL FRATE, D.F. FISHER
'In-flight Flow Visualization and Pressure Measurements on the NASA F-18 High Alpha Research Vehicle with Correlation to Ground Facility Results'

14 A. BERGMANN, D. HUMMEL, H.-Chr. OELKER
'Vortex Formation over a Close-coupled Canard-wing-body Configuration in Unsymmetrical Flow'

15 A. ELSENAAR, H.W.M. HOEIJMAKERS
'An Experimental Study of the Flow over a Sharp-edged Delta Wing at Subsonic, Transonic and Supersonic Speeds'

16 G. PAILHAS
'Experimental Investigation of a Boundary Layer Developing downstream of a Leading-edge Vortex'

Session IV – SLENDER-BODY VORTEX FLOWS

17 P. CHAMPIGNY, D. BAUDIN
'Ecoulement Tourbillonaire sur Fuselage de Missile. Etude Expérimentale et Modelisation

18 M. PIDD, J.H.B. SMITH
'Asymmetric Vortex Flow over Circular Cones'

19 I.R.M. MOIR
'Experimental Investigation of the Effect of Fineness Ratio on Lateral Force on a Pointed Slender Body of Revolution'

Session V – VORTEX DEVELOPMENT AND BREAKDOWN

20 J. DELERY
'Physique des Ecoulements Tourbillionaires'

21 R.C. NELSON, K.D. VISSER
'Breaking Down the Delta Wing Vortex – the Role of Vorticity in the Breakdown Process'

22 T.H. LÊ P. MÈGE, Y. MORCHOISNE
'Determination de Critères d'Eclatement Tourbillonaire par Résolution des Equations d'Euler et de Navier-Stokes'

23 D. PAGAN
'Etudes Fondementales sur l'Eclatement Tourbillonaire et son Contrôle'

24 S. AGRAWAL, R.M. BARNETT
'Investigation of Vortex Breakdown on a Delta Wing using Euler and Navier-Stokes Equations'

Session VI – VORTEX CONTROL

25 D.M. RAO
'Vortex Management for Tailoring Configuration Aerodynamics'

26 R. STAUFENBIEL
'On Aircraft Wake Properties and some Methods for Stimulating Decay and Breakdown of Tip Vortices'

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14. Abstract

Technical reviews of the papers from the AGARD Fluid Dynamics Panel Symposium on "Vortex Flow Aerodynamics" held 1st—4th October 1990 in Scheveningen, The Netherlands, are presented in this Technical Evaluation Report. In addition, some general comments, conclusions and recommendations are given regarding the relevance and success of the technical programme in meeting the needs of the aerospace community.

The principal emphasis of the Symposium was to provide results from recent technical programmes with the goal of improving the understanding and prediction of separation-induced vortex flows and their effects on vehicle performance, stability, control and structural design loads. To this end, 33 papers were selected covering four specific topics: vortex fundamentals, prediction and measurement of vortex flows including their modelling, application of vortex flows to the design and performance of aeroplanes, and unsteady aerodynamic effects associated with vortex flow movements in manoeuvring and oscillatory motions, instabilities and bursting.

The 33 papers announced for the meeting are available in AGARD Conference Proceedings CP-494 and are listed in the Appendix of this report.

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